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Optimization of on-off dampers for reducing collision of base-isolated buildings with retaining walls

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ABSTRACT

An optimized approach for initial clearance length, which is important when using on-off dampers in base-isolated buildings, is proposed. The influence of initial clearance length on the response of a superstructure model to seismic motion is investigated, given that the response may lead to collision with retaining walls. Furthermore, the optimization is configured to uniquely determine values of initial clearance lengths, which are used to minimize the responses of the superstructure model. An experiment is presented that uses a shaking table and on-off dampers with 28 combinations of initial clearance lengths. Comparison of the experimental results with those obtained from numerical analyses shows good agreement with respect to the solution of optimization.

Introduction

In Japan, seismic isolation systems are increasingly being used to mitigate damage to building structures during earthquakes, such as after the 1995 Hyogo-ken Nanbu earthquake. There is increasing apprehension about potentially large magnitude earthquakes focused offshore or such earthquakes occurring directly above their foci. Excessive deformation of the isolation layer in a building during a large magnitude earthquake may cause collision of the layer with retaining walls if the clearance between building and retaining wall is insufficient. This phenomenon should not be overlooked, especially in seismically isolated buildings which are expected to be highly resistant to earthquakes. Adding passive dampers is effective during huge magnitude earthquakes, but they also increase response acceleration during design earthquakes and lower the performance of the seismic isolation structure. In this paper we propose a new damper,

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referred to as an on-off damper, that can vary the damping force depending on the response displacement and response velocity [1–2] (Fig. 1). The on-off damper has an elongated hole at the support joint, resulting in the joint only coming into contact with the edge of the loose hole when the response displacement exceeds a certain value. This pushes or pulls the cylinder to attenuate the earthquake force. The design involves a simple modification of the shape of the pin support in existing oil dampers, and requires only slight modification of existing attenuators. The efficacy and effects of using the proposed attenuator have been examined in terms of the responses of a superstructure model to seismic forces which can cause the isolation layer to collide with the retaining walls. However, determination of the elongated hole lengths (referred to here as initial clearance lengths) and their influence has not been well-established. In this paper, an optimization approach is presented for the initial clearance length, which is found to be crucial in the on-off damper. In particular, the aim is to optimize the initial clearance length to minimize or prevent the response of a superstructure resulting in collision with retaining walls. To achieve this, the initial clearance lengths were uniquely determined, to minimize the responses of the superstructure model, and a shaking table experiment with on-off dampers with 28 combinations of initial clearance lengths was conducted. The optimization solutions are compared with the test results.

Figure 1. On-off damper used in shaking table tests. Note the elongated hole in the damper joint, with initial clearance length (l) shown.

Shaking Table Test

Experimental setup

The experimental model is a four-story structure with a base isolation layer (Fig. 2) and damping devices installed on the base isolation layer. The precise specifications and initial magnetorheological (MR) dampers are described in Kishida et al., 2017 [1]. The MR damper was carefully controlled to simulate an oil damper with bilinear hysteresis. The additional dampers were on-off dampers with damping coefficient (c) of 1.96 kN s/m. The adjustable initial clearance length (l) of the on-off dampers was in the 0–30 mm range. The oil dampers in the on-off dampers have linear viscous damping force characteristics, and two on-off dampers were set at the base isolation layer. The input accelerations into the model were estimated pulse waveforms of earthquakes predicted to occur along the Uemachi fault in Osaka, Japan (referred to as level-3C earthquakes [3]), and three observed earthquakes (El Centro 1940 NS, Hachinohe 1968 NS, JMA Kobe 1995 NS) normalized to a maximum velocity of 50 cm/s (level-2 earthquakes). Level-3C pulse waves with periods of 1, 2, and 3 s (denoted as Tp1, Tp2, and Tp3, respectively) were used. The time history waveforms of the input accelerations are shown in Fig.

3. The similarity ratio of the length between test and model was 1:4, and time was condensed to half the original signal length. A pneumatic cylinder, with 2 kN of output resultant force, represents the retaining wall in Fig. 2 and the cylinders are attached at both sides. The clearance between the test specimen and cylinder was set to 100 mm.

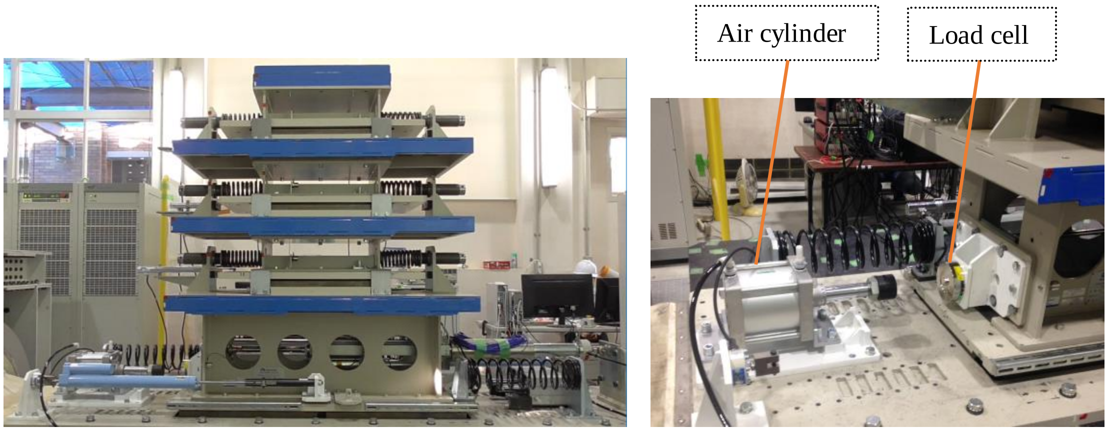

Figure 2. Experimental setup showing the four-story test structure (left panel) and pneumatic cylinder with load cell (right panel).

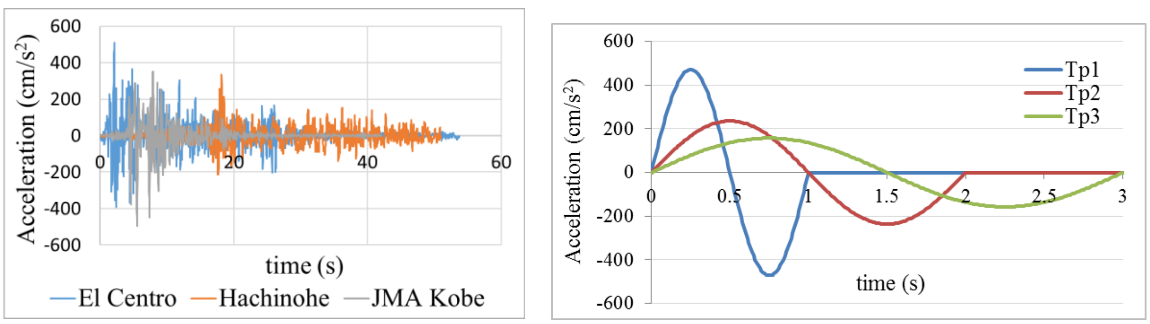

Figure 3. Time history waveforms of input accelerations from three observed earthquakes (El Centro 1940, Hachinohe 1968, and JMA Kobe 1995) and pulse waves of 1, 2, and 3 s (Tp1, Tp2, and Tp3, respectively).

Combinations of initial clearance lengths

Two on-off dampers were installed at the base isolation layer as additional dampers. Each of the initial clearance lengths (in mm) of two on-off dampers are denoted as l_1 and l_2, respectively, and combinations of l_1 and l_2 are as follows:

(l_1, l_2) = (0,0), (0,5), (0,10), (0,15), (0,20), (0,25), (0,30),
(5,5), (5,10), (5,15), (5,20), (5,25) , (5,30),
(10,10), (10,15), (10,20), (10,25) , (10,30),
(15,15), (15,20), (15,25) , (15,30),
(20,20), (20,25) , (20,30),
(25,25) , (25,30),
(30,30)

Test results

When the Tp1 pulse wave was inputted, the displacement of the isolation layer did not exceed the clearance and the test specimen did not collide with the air cylinders, because of friction between the specimen and the shaking table. On the other hand, according to previous numerical analysis simulations, the collision occurred on the Tp1 pulse wave. Because the collision phenomena were different between the experiment and the analysis, the Tp1 pulse wave was excluded. Results in response to the Tp2 and Tp3 pulse wave for the level-3C pulse waves, and results in response to El Centro and JMA Kobe earthquake for the level-2 observed earthquakes, are shown below.

The response ratios are defined as the maximum response with on-off dampers divided by the maximum response without on-off dampers. Table 1 shows the response ratios for the absolute acceleration in response to level-2 earthquake input, with various combinations of initial clearance lengths. The maximum absolute accelerations (m/s^2) without on-off dampers are shown together, and the maximum response ratio for each floor is denoted by gray shading.

Table 1 (a). Response ratios of absolute acceleration in response to level-2 El Centro earthquake input, with various combinations of initial clearance length. Gray shading indicates the maximum response ratio for each floor.

Floor	no on-off dampers (m/s^2)	(l_1, l_2)												
		(0,0)	(0,5)	(0,10)	(0,15)	(0,20)	(0,25)	(0,30)	(5,5)	(5,10)	(5,15)	(5,20)	(5,25)	(5,30)
1	1.49	1.57	2.28	2.30	1.64	1.28	1.69	1.32	2.33	2.32	2.58	2.33	2.22	1.99
2	1.37	1.50	1.38	1.36	1.38	1.21	1.31	1.27	1.21	1.15	1.17	1.15	1.18	1.09
3	1.06	1.41	1.51	1.45	1.37	1.34	1.31	1.39	1.41	1.40	1.34	1.35	1.30	1.31
4	1.64	1.18	1.12	1.10	1.05	1.06	1.02	1.06	1.16	1.19	1.11	1.12	1.14	1.15

Floor	(10,10)	(10,15)	(10,20)	(10,25)	(10,30)	(15,15)	(15,20)	(15,25)	(15,30)	(20,20)	(20,25)	(20,30)	(25,25)	(25,30)	(30,30)
1	2.19	1.78	1.63	1.64	1.68	2.17	2.10	1.77	1.98	1.41	1.31	1.18	1.12	1.11	1.31
2	1.21	1.20	1.16	1.16	1.13	1.11	1.16	1.08	1.13	1.09	1.03	1.07	1.03	1.08	1.08
3	1.50	1.47	1.27	1.28	1.28	1.37	1.28	1.25	1.24	1.22	1.24	1.15	1.21	1.16	1.14
4	1.24	1.17	1.11	1.08	1.12	1.06	1.08	1.06	1.06	1.02	1.05	1.07	1.03	1.03	1.09

Table 1 (b). Response ratios of absolute acceleration in response to level-2 JMA Kobe earthquake input, with various combinations of initial clearance length.

Floor	no on-off dampers (m/s^2)	(0,0)	(0,5)	(0,10)	(0,15)	(0,20)	(0,25)	(0,30)	(5,5)	(5,10)	(5,15)	(5,20)	(5,25)	(5,30)
1	1.91	1.45	1.59	1.23	1.28	1.23	1.24	1.23	2.08	1.66	1.86	1.83	1.81	1.67
2	1.61	1.36	1.23	1.22	1.22	1.22	1.18	1.23	1.30	1.19	1.23	1.16	1.14	1.19
3	1.35	1.32	1.17	1.18	1.15	1.13	1.12	1.11	1.25	1.18	1.14	1.13	1.09	1.13
4	2.42	1.31	1.20	1.18	1.18	1.17	1.16	1.17	1.25	1.16	1.18	1.13	1.12	1.16

Floor	(10,10)	(10,15)	(10,20)	(10,25)	(10,30)	(15,15)	(15,20)	(15,25)	(15,30)	(20,20)	(20,25)	(20,30)	(25,25)	(25,30)	(30,30)
1	1.31	1.23	1.07	1.13	1.12	1.11	1.08	1.05	1.04	1.04	1.06	1.05	1.05	1.05	1.07
2	1.07	1.06	1.06	1.03	1.08	1.12	1.11	1.06	1.05	1.08	1.08	1.07	1.05	1.06	1.08
3	1.07	1.02	1.03	1.00	1.06	1.06	1.05	1.03	1.02	1.00	1.02	1.02	1.02	1.03	1.05
4	1.10	1.06	1.06	1.05	1.09	1.10	1.08	1.05	1.04	1.03	1.05	1.01	1.04	1.04	1.07

When the combination of initial clearance lengths is (l_1, l_2) = (0,0), the absolute acceleration responses increase for all floors compared with the case without on-off dampers. This is especially noticeable in the increasing responses at the 2nd, 3rd and 4th floors. The responses at the 1st floor for combinations of low initial clearance length, where (l_1, l_2) = (5,5), (5,15), are larger than in a case of (l_1, l_2) = (0,0). The combinations of large initial clearance length, such as where (l_1, l_2) = (25,25), (25,30), do not significantly increase the responses.

Table 2 shows the response ratios for relative story displacement related to level-2 earthquake input, with various combinations of initial clearance length. The maximum relative story displacements (mm) without on-off dampers are shown together, and the maximum response ratio for each floor is denoted by gray shading. The relative story displacements at the isolation layer (between ground floor and 1st floor) decrease compared with the case without on-off dampers. The maximum response at the isolation layer occurs when (l_1, l_2) = (0,30), (30,30). The relative displacements at the upper inter-stories increase for combinations of low initial clearance length.

Table 2 (a). Response ratios of relative story displacement related to level-2 El Centro earthquake input, with various combinations of initial clearance length.

Story	no on-off dampers (mm)	(0,0)	(0,5)	(0,10)	(0,15)	(0,20)	(0,25)	(0,30)	(5,5)	(5,10)	(5,15)	(5,20)	(5,25)	(5,30)
0-1	31.04	0.75	0.89	0.88	0.80	0.89	0.93	0.94	0.81	0.80	0.84	0.83	0.87	0.88
1-2	6.33	1.36	1.41	1.38	1.30	1.22	1.29	1.24	1.36	1.42	1.38	1.29	1.27	1.32
2-3	8.56	1.32	1.36	1.37	1.28	1.25	1.25	1.26	1.34	1.36	1.30	1.29	1.25	1.24
3-4	4.98	1.26	1.05	1.14	1.06	0.94	1.05	0.95	1.26	1.31	1.25	1.08	1.10	1.03

Story	(10,10)	(10,15)	(10,20)	(10,25)	(10,30)	(15,15)	(15,20)	(15,25)	(15,30)	(20,20)	(20,25)	(20,30)	(25,25)	(25,30)	(30,30)
0-1	0.82	0.88	0.90	0.90	0.90	0.90	0.90	0.88	0.89	0.89	0.90	0.88	0.89	0.90	0.92
1-2	1.46	1.43	1.29	1.30	1.34	1.35	1.28	1.22	1.23	1.12	1.11	1.07	1.08	1.11	1.10
2-3	1.39	1.34	1.24	1.26	1.28	1.25	1.23	1.20	1.19	1.16	1.15	1.12	1.12	1.12	1.11
3-4	1.32	1.27	1.06	1.10	1.10	0.95	0.95	0.93	0.91	0.93	0.96	0.83	0.91	0.79	0.83

Table 2 (b). Response ratios of relative story displacement related to level-2 JMA Kobe earthquake input, with various combinations of initial clearance length.

Story	no on-off dampers (mm)	(0,0)	(0,5)	(0,10)	(0,15)	(0,20)	(0,25)	(0,30)	(5,5)	(5,10)	(5,15)	(5,20)	(5,25)	(5,30)
0-1	21.10	0.80	0.86	0.87	0.86	0.90	0.89	0.92	0.81	0.80	0.83	0.95	0.87	0.87
1-2	7.36	1.29	1.24	1.22	1.14	1.15	1.12	1.18	1.24	1.21	1.17	1.14	1.13	1.15
2-3	9.50	1.37	1.27	1.24	1.25	1.21	1.23	1.22	1.27	1.20	1.19	1.16	1.14	1.17
3-4	7.13	1.45	1.34	1.28	1.30	1.29	1.27	1.30	1.34	1.26	1.25	1.20	1.19	1.22

Story	(10,10)	(10,15)	(10,20)	(10,25)	(10,30)	(15,15)	(15,20)	(15,25)	(15,30)	(20,20)	(20,25)	(20,30)	(25,25)	(25,30)	(30,30)
0-1	0.84	0.88	0.90	0.94	0.93	0.93	0.93	0.93	0.95	0.95	0.98	0.96	0.98	0.97	1.02
1-2	1.20	1.12	1.10	1.10	1.18	1.15	1.10	1.05	1.05	1.05	1.07	1.05	1.03	1.07	1.06
2-3	1.13	1.09	1.08	1.07	1.11	1.13	1.10	1.07	1.08	1.06	1.07	1.06	1.05	1.08	1.09
3-4	1.13	1.09	1.10	1.07	1.16	1.18	1.14	1.10	1.10	1.07	1.09	1.07	1.07	1.09	1.11

Tables 3 and 4 show the response ratios for the absolute acceleration and relative story displacement related to level-3C pulse wave input with various combinations of initial clearance lengths, respectively. The minimum response ratio for each floor is denoted by pale gray shading and the maximum response ratio is denoted by dark gray shading. All responses decrease in comparison with cases without on-off dampers, especially in cases with combinations of low initial clearance lengths.

Conversely, in cases with combinations of large initial clearance lengths, the responses do not decrease effectively. The acceleration of the 1st floor for the case of the same initial clearance length combination tends to be larger than for a case with different initial clearance length combination. For example, the acceleration of the 1st floor for (l_1, l_2) = (5,5) is larger than that for (l_1, l_2) = (5,10), and (l_1, l_2) = (10,10) is larger than that for (l_1, l_2) = (10,25). This phenomenon can be explained as follows: when the joint of the on-off dampers collides with the edge of the loose hole at the same time, the acceleration of the 1st floor increases, but when the joint collides in a stepwise manner, the acceleration of the 1st floor is reduced.

Table 3 (a). Response ratios of absolute acceleration related to level-3C Tp2 pulse wave input, with various combinations of initial clearance length. Pale gray shading indicates the minimum response ratio for each floor, and dark gray shading indicates the maximum response ratio.

Floor	no on-off dampers (m/s^2)	(0,0)	(0,5)	(0,10)	(0,15)	(0,20)	(0,25)	(0,30)	(5,5)	(5,10)	(5,15)	(5,20)	(5,25)	(5,30)
1	13.98	0.23	0.31	0.38	0.35	0.42	0.44	0.32	0.41	0.37	0.37	0.45	0.39	0.38
2	5.89	0.36	0.39	0.43	0.49	0.49	0.50	0.46	0.50	0.49	0.50	0.50	0.53	0.52
3	6.71	0.42	0.43	0.44	0.44	0.45	0.47	0.46	0.44	0.45	0.46	0.46	0.48	0.48
4	7.08	0.44	0.48	0.49	0.49	0.49	0.49	0.47	0.52	0.53	0.52	0.53	0.52	0.52

Floor	(10,10)	(10,15)	(10,20)	(10,25)	(10,30)	(15,15)	(15,20)	(15,25)	(15,30)	(20,20)	(20,25)	(20,30)	(25,25)	(25,30)	(30,30)
1	0.44	0.43	0.48	0.34	0.33	0.33	0.36	0.30	0.33	0.39	0.37	0.32	0.41	0.47	0.36
2	0.51	0.53	0.53	0.53	0.53	0.52	0.52	0.54	0.54	0.54	0.51	0.55	0.56	0.55	0.54
3	0.46	0.48	0.50	0.49	0.48	0.49	0.51	0.52	0.54	0.53	0.53	0.56	0.58	0.59	0.57
4	0.52	0.51	0.52	0.53	0.51	0.51	0.50	0.52	0.52	0.54	0.52	0.55	0.57	0.57	0.56

Table 3 (b). Response ratios of absolute acceleration related to level-3C Tp3 pulse wave input, with various combinations of initial clearance length.

Floor	no on-off dampers (m/s^2)	(0,0)	(0,5)	(0,10)	(0,15)	(0,20)	(0,25)	(0,30)	(5,5)	(5,10)	(5,15)	(5,20)	(5,25)	(5,30)
1	8.76	0.19	0.19	0.19	0.27	0.23	0.32	0.28	0.19	0.19	0.20	0.22	0.19	0.25
2	5.34	0.33	0.32	0.33	0.33	0.35	0.34	0.37	0.32	0.32	0.33	0.34	0.34	0.36
3	5.55	0.31	0.34	0.36	0.37	0.38	0.41	0.41	0.34	0.37	0.39	0.39	0.41	0.42
4	8.33	0.21	0.24	0.26	0.28	0.30	0.31	0.32	0.25	0.28	0.31	0.30	0.33	0.33

Floor	(10,10)	(10,15)	(10,20)	(10,25)	(10,30)	(15,15)	(15,20)	(15,25)	(15,30)	(20,20)	(20,25)	(20,30)	(25,25)	(25,30)	(30,30)
1	0.19	0.23	0.21	0.24	0.27	0.27	0.27	0.25	0.28	0.43	0.35	0.36	0.45	0.38	0.42
2	0.35	0.35	0.36	0.36	0.35	0.34	0.35	0.36	0.36	0.37	0.38	0.39	0.39	0.46	0.55
3	0.39	0.40	0.41	0.42	0.43	0.41	0.42	0.43	0.44	0.44	0.44	0.46	0.47	0.50	0.54
4	0.31	0.34	0.35	0.36	0.36	0.35	0.36	0.37	0.36	0.38	0.39	0.40	0.40	0.42	0.44

Table 4 (a). Response ratios of relative story displacement related to level-3C Tp2 pulse wave input, with various combinations of initial clearance length.

Story	no on-off dampers (mm)	(0,0)	(0,5)	(0,10)	(0,15)	(0,20)	(0,25)	(0,30)	(5,5)	(5,10)	(5,15)	(5,20)	(5,25)	(5,30)
0-1	117.67	0.88	0.84	0.89	0.90	0.91	0.91	0.91	0.90	0.91	0.91	0.91	0.91	0.92
1-2	33.11	0.64	0.64	0.65	0.65	0.66	0.68	0.67	0.66	0.67	0.68	0.68	0.72	0.73
2-3	38.70	0.55	0.56	0.58	0.59	0.60	0.61	0.60	0.57	0.58	0.60	0.60	0.62	0.63
3-4	24.46	0.43	0.44	0.48	0.49	0.48	0.50	0.49	0.50	0.51	0.50	0.52	0.49	0.50

Story	(10,10)	(10,15)	(10,20)	(10,25)	(10,30)	(15,15)	(15,20)	(15,25)	(15,30)	(20,20)	(20,25)	(20,30)	(25,25)	(25,30)	(30,30)
0-1	0.91	0.92	0.92	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.94	0.94	0.94	0.94	0.94
1-2	0.67	0.69	0.73	0.72	0.73	0.70	0.74	0.75	0.77	0.77	0.75	0.78	0.79	0.81	0.80
2-3	0.60	0.61	0.61	0.63	0.64	0.62	0.62	0.65	0.66	0.66	0.65	0.66	0.66	0.67	0.68
3-4	0.48	0.48	0.49	0.51	0.49	0.48	0.49	0.51	0.51	0.53	0.54	0.55	0.56	0.58	0.55

Table 4 (b). Response ratios of relative story displacement related to level-3C Tp3 pulse wave input, with various combinations of initial clearance length.

Story	no on-off dampers (mm)	(0,0)	(0,5)	(0,10)	(0,15)	(0,20)	(0,25)	(0,30)	(5,5)	(5,10)	(5,15)	(5,20)	(5,25)	(5,30)
0-1	121.46	0.73	0.71	0.73	0.74	0.73	0.75	0.75	0.75	0.75	0.76	0.76	0.78	0.79
1-2	32.20	0.48	0.47	0.50	0.51	0.53	0.51	0.52	0.50	0.51	0.52	0.52	0.53	0.52
2-3	42.79	0.34	0.35	0.35	0.36	0.38	0.37	0.39	0.35	0.36	0.38	0.38	0.40	0.40
3-4	25.23	0.21	0.25	0.27	0.30	0.28	0.33	0.32	0.26	0.29	0.33	0.32	0.35	0.36

Story	(10,10)	(10,15)	(10,20)	(10,25)	(10,30)	(15,15)	(15,20)	(15,25)	(15,30)	(20,20)	(20,25)	(20,30)	(25,25)	(25,30)	(30,30)
0-1	0.74	0.77	0.79	0.79	0.80	0.77	0.78	0.79	0.80	0.78	0.86	0.80	0.81	0.82	0.82
1-2	0.54	0.54	0.55	0.55	0.54	0.54	0.56	0.57	0.56	0.56	0.58	0.57	0.58	0.59	0.60
2-3	0.37	0.39	0.40	0.41	0.42	0.39	0.41	0.42	0.42	0.41	0.43	0.43	0.43	0.44	0.47
3-4	0.32	0.36	0.39	0.39	0.40	0.38	0.40	0.42	0.42	0.43	0.46	0.44	0.46	0.49	0.50

Optimization approach

Configuration of optimization strategy

When designing the on-off dampers, the initial clearance length needed to minimize the response of the structure to earthquakes was determined. We selected the response ratios as the response to minimize. The optimization strategy was undertaken as follows: find values of l_1, l_2 to minimize the objective function (F) when the structure is subjected to $0 \leq l_i \leq 30$. The objective function (F) is thus configured as follows:

$$F = \alpha_2 \sum R_{2ij} + \alpha_{3\mathrm{C}} \sum R_{3\mathrm{C}ij} \tag{1}$$

in which α_2 and $\alpha_{3\mathrm{C}}$ are weighted coefficients used to multiply the response ratio for level-2 and level-3C earthquakes, respectively. R_{2ij} is the response ratio of the i-th story for the j-th level-2 observed earthquake and $R_{3\mathrm{C}ij}$ is the response ratio of the i-th story for the j-th level-3C pulse wave. The reproduction periods of level-2 and level-3C earthquakes are assumed to be 500 and 1000 years respectively. Thus values of α_2 and $\alpha_{3\mathrm{C}}$ were set to 0.663 and 0.337, respectively, given the probability of exceedance in 30 years. The objective functions in the following five cases were investigated:

1. $$F_1 = \alpha_2 \sum_{i=1}^{4} \left(R_{i(\mathrm{El})} + R_{i(\mathrm{Kb})} \right) + \alpha_{3\mathrm{C}} \sum_{i=1}^{4} \left(R_{i(\mathrm{Tp2})} + R_{i(\mathrm{Tp3})} \right) \tag{2}$$

2. $$F_2 = \alpha_2 \sum_{i=1}^{4} R_{i(\mathrm{El})} + \alpha_{3\mathrm{C}} \sum_{i=1}^{4} R_{i(\mathrm{Tp2})} \tag{3}$$

3. $$F_3 = \alpha_2 \sum_{i=1}^{4} R_{i(\mathrm{Kb})} + \alpha_{3\mathrm{C}} \sum_{i=1}^{4} R_{i(\mathrm{Tp2})} \tag{4}$$

4. $$F_4 = \alpha_2 \sum_{i=1}^{4} R_{i(\mathrm{El})} + \alpha_{3\mathrm{C}} \sum_{i=1}^{4} R_{i(\mathrm{Tp3})} \tag{5}$$

5. $$F_5 = \alpha_2 \sum_{i=1}^{4} R_{i(\mathrm{Kb})} + \alpha_{3\mathrm{C}} \sum_{i=1}^{4} R_{i(\mathrm{Tp3})} \tag{6}$$

in which $R_{i(\mathrm{E1})}$ and $R_{i(\mathrm{Kb})}$ are the response ratios for the level-2 El Centro and JMA Kobe earthquakes, respectively. $R_{i(\mathrm{Tp2})}$ and $R_{i(\mathrm{Tp3})}$ are the response ratios for the level-3C Tp2 pulse wave and Tp3 pulse wave, respectively. The objective function for the absolute acceleration is F_{iacc} and that for the relative story displacement is F_{idsp}.

Optimization results

A pattern search (direct search) algorithm was used to solve the optimization problem. This method does not require any information about the gradient of the objective function [4]. Table 5 shows the solution and objective function value at the solution for each objective function. The numerical analysis model used to calculate the responses was derived from Kishida et al., 2017 [1]. The air cylinder was modeled with constant output force (2 kN) during touching of the specimen.

Table 5. Objective function and solution values at each objective function solution.

Objective function	Solution (l_1, l_2)	Objective function value at solution
$F_{1\mathrm{acc}}$	(19.7 , 21.6)	7.68
$F_{1\mathrm{dsp}}$	(15.1 , 23.2)	7.40
$F_{2\mathrm{acc}}$	(27.1 , 28.5)	3.93
$F_{2\mathrm{dsp}}$	(28.5 , 28.5)	3.84
$F_{3\mathrm{acc}}$	(13.5 , 29.6)	3.88
$F_{3\mathrm{dsp}}$	(14.0 , 14.0)	3.76
$F_{4\mathrm{acc}}$	(19.7 , 26.1)	3.76
$F_{4\mathrm{dsp}}$	(19.7 , 27.8)	3.59
$F_{5\mathrm{acc}}$	(14.0 , 14.1)	3.64
$F_{5\mathrm{dsp}}$	(14.0 , 14.1)	3.42

Comparison with experimental results

Objective function values calculated from the shaking table test results are shown in Table 6 for all combinations of initial clearance lengths. The minimum values are denoted by gray shading, and these values are similar to the solutions of optimization, except for cases of objective functions F_{1acc} and F_{1dsp}.

When the objective functions consist of response ratios of one earthquake for level-2 and one pulse wave for level-3C earthquake, respectively, the minimum objective function values from test results accord well with the solutions of optimization. Thus, the configuration methods of the objective function should be investigated further.

Conclusions

1) An optimization approach for the initial clearance length of on-off dampers in base-isolated buildings is proposed. Solutions of optimization were compared with results obtained from shaking table tests with 28 combinations of initial clearance lengths. The solutions from the optimization accord well with the test results in cases where the objective functions are calculated by the sum of the response ratios. This optimization method allows us to determine the initial clearance length of on-off dampers uniquely without analyzing by trial and error.

2) Experimental results show that the acceleration of the 1st floor, in cases with different initial clearance length combinations, tends to decrease compared with cases with the same initial clearance length combinations subjected to level-3C pulse waves. This is because the joint of the on-off dampers collides with the edge of the loose hole in a stepwise manner.

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Table 6. Objective function values calculated from test results.

$F_{1\mathrm{acc}}$		l_2						
		0	5	10	15	20	25	30
	0	8.19	8.52	8.28	7.83	7.43	7.75	7.52
	5		8.95	8.47	8.73	8.49	8.37	8.19
	10			8.16	7.72	7.35	7.31	7.44
l_1	15				7.78	7.70	7.31	7.48
	20		sym.			7.11	7.04	6.93
	25						6.97	7.01
	30							7.24

$F_{1\mathrm{dsp}}$		l_2						
		0	5	10	15	20	25	30
	0	7.80	7.68	7.73	7.48	7.41	7.56	7.54
	5		7.76	7.74	7.68	7.50	7.47	7.52
	10			7.72	7.63	7.40	7.46	7.64
l_1	15				7.48	7.38	7.26	7.27
	20		sym.			7.16	7.28	7.07
	25						7.16	7.19
	30							7.27

$F_{2\mathrm{acc}}$		l_2						
		0	5	10	15	20	25	30
	0	4.23	4.72	4.70	4.20	3.86	4.17	3.92
	5		4.68	4.64	4.74	4.59	4.52	4.31
	10			4.72	4.38	4.11	4.06	4.08
l_1	15				4.40	4.36	4.06	4.23
	20		sym.			3.81	3.73	3.63
	25						3.62	3.64
	30							3.75

$F_{2\mathrm{dsp}}$		l_2						
		0	5	10	15	20	25	30
	0	3.95	3.96	4.04	3.83	3.75	3.90	3.81
	5		4.05	4.14	4.07	3.88	3.90	3.90
	10			4.20	4.17	3.91	3.96	4.00
l_1	15				3.87	3.83	3.76	3.76
	20		sym.			3.69	3.70	3.57
	25						3.64	3.61
	30							3.62

$F_{3\mathrm{acc}}$		l_2						
		0	5	10	15	20	25	30
	0	4.09	3.98	3.78	3.80	3.77	3.75	3.71
	5		4.53	4.06	4.20	4.13	4.07	4.06
	10			3.67	3.55	3.48	3.43	3.51
l_1	15				3.54	3.50	3.41	3.40
	20		sym.			3.43	3.44	3.42
	25						3.48	3.51
	30							3.51

$F_{3\mathrm{dsp}}$		l_2						
		0	5	10	15	20	25	30
	0	4.10	3.96	3.94	3.90	3.91	3.90	3.96
	5		3.97	3.85	3.85	3.87	3.79	3.86
	10			3.75	3.67	3.70	3.71	3.85
l_1	15				3.83	3.76	3.71	3.73
	20		sym.			3.71	3.76	3.73
	25						3.74	3.80
	30							3.84

$F_{4\mathrm{acc}}$		l_2						
		0	5	10	15	20	25	30
	0	4.10	4.54	4.50	4.03	3.67	4.00	3.81
	5		4.42	4.41	4.53	4.36	4.30	4.13
	10			4.49	4.17	3.87	3.88	3.93
l_1	15				4.24	4.20	3.90	4.07
	20		sym.			3.68	3.60	3.51
	25						3.49	3.50
	30							3.72

$F_{4\mathrm{dsp}}$		l_2						
		0	5	10	15	20	25	30
	0	3.69	3.72	3.79	3.59	3.50	3.66	3.58
	5		3.79	3.89	3.83	3.64	3.67	3.66
	10			3.97	3.96	3.70	3.75	3.79
l_1	15				3.65	3.62	3.55	3.54
	20		sym.			3.46	3.52	3.34
	25						3.42	3.39
	30							3.43

$F_{5\mathrm{acc}}$		l_2						
		0	5	10	15	20	25	30
	0	3.95	3.81	3.57	3.62	3.57	3.58	3.60
	5		4.27	3.83	3.99	3.90	3.85	3.88
	10			3.44	3.34	3.24	3.26	3.36
l_1	15				3.38	3.34	3.25	3.24
	20		sym.			3.30	3.31	3.30
	25						3.34	3.37
	30							3.49

$F_{5\mathrm{dsp}}$		l_2						
		0	5	10	15	20	25	30
	0	3.85	3.72	3.69	3.66	3.67	3.66	3.73
	5		3.72	3.60	3.61	3.62	3.56	3.62
	10			3.52	3.46	3.49	3.49	3.63
l_1	15				3.61	3.55	3.50	3.51
	20		sym.			3.47	3.58	3.50
	25						3.51	3.57
	30							3.64